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Active low-grade energy recovery potential for building energy conservation

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ABSTRACT

With environmental protection and energy source posing as the biggest issue of the global problems, human beings have no choice but to reduce energy consumption. One way to accomplish this is to increase the efficiency of energy consumption and sufficiently exploit the low-grade energy in our lives. Low-grade energy recovery devices are of significance to meet the needs for energy conservation and green environment requirements such as fresh air pre cooling/heating, water heating, drying clothes and humidifying. These devices are also free of motion parts, non-corrosive and environmentally friendly. Various low-grade energy recoveries powered cooling, heating, drying and dehumidifying systems have been tested extensively; however, these systems are not yet ready to compete with the well-known vapor-compression system. The objective of this paper is to provide fundamental knowledge on the low-grade energy usage systems and present a detailed review on the past efforts in the field of low-grade energy recovery and usage subsystems. Lots of attempts have been made by the researchers to improve the performance of the low-grade energy recovery or usage subsystems. It is seen that, for successful operation of such systems, combination of diverse technologies is essential for more effective and multi-purpose applications.

Contents

1. Introduction

Nowadays, energy security, economic growth and environment protection are the national energy policy drivers of any country. As world populations grow, faster than the average 2%, the need for more and more energy is exacerbated. Actually, people cost their most of life time within buildings. Hence, the purpose behind the building energy consumption is to provide a variety of building services, which include weather protection, storage, communications, thermal comfort, facilities of daily living, aesthetics, work environment etc. That is to say, by the consumption of energy, buildings are to provide an acceptable indoor environment, which allows occupants to carry out various activities.

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Globally, buildings are responsible for approximately 40% of the total world annual energy consumption. Therefore, the building sector is a major consumer of both energy and materials worldwide, and that consumption is increasing continuously. Within the buildings, most of energy is for the provision of heating, cooling and air conditioning [1]. For space heating, for example, drawing the boundary as far as the boiler or heat pump implies that the service considered is delivery of heat to a room or building. Extending the boundary to cover an entire building implies that the unit of service is maintaining a desired temperature distinct from the outside. The minimum work needed to achieve this task depends on additional factors such as insulation and the degree of venting with the outdoors needed to maintain air quality [2]. For air conditioning, buildings in warm climates or those with high casual gains may need some form of cooling to maintain a comfortable interior environment [3–7].

The heating or cooling of an enclosed space to maintain thermal comfort is a highly energy intensive process accounting for as much as 60–70% of total energy. In naturally ventilated buildings, one way to achieve this is by precooling supply air, using a form of chiller attached to the inflow vent of the building. Hence, maximum natural energy or recycling waste heat or coolness can be used for creating a pleasant environment inside the built envelope [8]. When the interior is required to be warmer than the outside, the incoming exterior air would be heated. This situation may occur in winter. However, when the exterior temperature is sufficiently high (sufficiently low), as in summer (winter), the room should be kept cooler (warmer) than ambient air environment to achieve indoor thermal comfort, which cannot be implemented simply by the use of natural ventilation. Usually, there are air conditioners or heat pumps employed to achieve that required thermal comfort of indoor air. Absolutely, directly intake of ambient fresh air into the indoor space will greatly enhance the indoor air quality; on the other hand, the heat exchange between fresh air and indoor air unexpectedly increase the heating/cooling load across the buildings. Fortunately, some novel methods or units have been presented in recent years, and these will be reviewed in the present paper.

In addition to the energy consumption by building air conditioning, lots of other facilities, including domestic equipments, traffic tools, and electronics, should 'eat' the fuels, particularly the fossil fuels. As you know, fossil fuels currently supply most of the world's energy needs, and however acceptable their long-term consequences, the supplies are likely to remain adequate for the next few generations. Scientists and policy makers must make use of this period of grace to promote energy conservation or recovery from low-grade heat sources of energy and determine what is scientifically possible, environmentally acceptable and technologically promising [9]. Actually, energy use reduction can be achieved by minimizing the energy demand, by rational energy use, by recovering heat and cold and by using energy from the ambient air and from the ground [1]. In past 20 years, researchers of this paper have created lots of novel heat/cold recovery units; these will be overviewed in the present work.

Therefore, thermal recovery from building air conditioners and low-grade waste heat recovery methods will be reviewed and discussed in the present work. In details, this paper will review technologies of heat and cold recovery and efficient energy use from the ambient air for built environment and services, with most of them being experimentally and theoretically studied by the authors. In Section 2, waste heat and cold recovery in air-conditioning systems for improving indoor environment are introduced; In Section 3, thermoelectric technologies as clothes dryer, ventilator, vehicle air conditioning, electronic cooler and dehumidifier with energy from the ambient air are indicated; finally, conclusions are drawn in Section 4.

2. Waste heat and cold recovery facility in air-conditioning room

The quest to accomplish a safe and comfortable environment has always been one of the main preoccupations of human beings. In ancient times, people used experience gained over many years to make the best use of available resources to achieve adequate living conditions. At late as the 1960s though, house comfort conditions were only for the few. From then onward air-conditioning systems became common in many countries due to the development of mechanical refrigeration and the rise of the standard of living. During recent years research aimed at the development of technologies than can offer reductions in energy consumption, peak electrical demand and energy costs without lowering the desired level of comfort conditions has intensified [10].

In terms of air conditioning, building ventilation is necessary for supporting life by maintaining acceptable levels of oxygen in the air, to prevent carbon dioxide from rising to unacceptably high concentrations and to remove odour, moisture and pollution produced internally. The method of building ventilation is so important in influencing not only the air quality in the occupied zone but also the cooling or heating energy requirement for the space. The ventilation rate required for a given room or a building is determined to satisfy both health and comfort criteria. In modern and retrofit buildings, ventilation is probably the greatest component of the total energy consumption. This is usually in

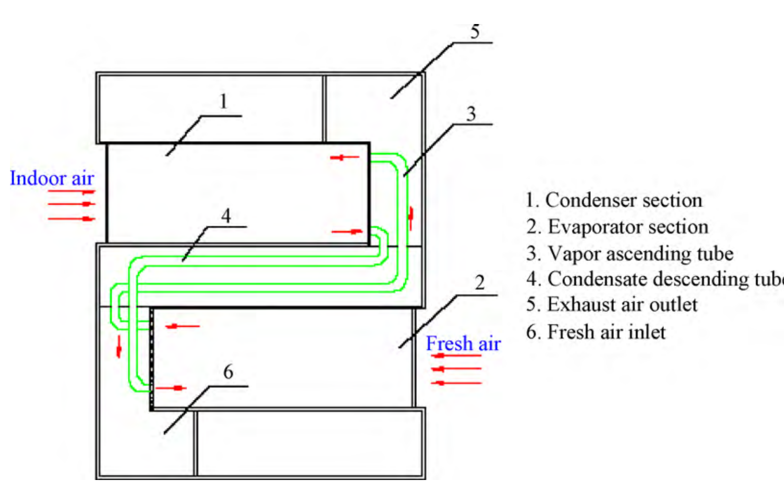


Fig. 1. Schematic configuration of heat pipe heat recovery facility from Liu et al. [7].

Fig. 2. Prototype of separate heat pipe heat recovery facility from Liu [15].

the range of 30–60% of the building energy consumption. The large proportion of ventilation energy is due to the three main reasons. Firstly, modern buildings are generally well insulated and, therefore, the heat gain or loss through the fabric is low. Secondly, modern building materials and furnishings emit large amounts of VOCs and TVOCs and so it becomes necessary to dilute their concentration by supplying greater ventilation rates to these buildings. The third cause is as a result of the recent concern regarding the sick building syndrome and other building related illnesses which have influenced HVAC designers to improve the indoor air quality by specifying greater quantities of fresh air supply [11]. In mechanically ventilated buildings, heat recovery from ventilation air is the single most important means of reducing ventilation energy consumption. Many different types of heat recovery systems are available for transferring energy from the exhaust air to the supply air or vice versa [3–7,12,13]. This section just reviews some combining heat recovery window-type air conditioners in residential buildings, i.e., separate heat pipe window-type air conditioner and membrane-based total heat recovery ventilator.

2.1. Separate heat pipe heat recovery window-type air conditioner

A two-phase thermosyphon loop heat recovery facility has been developed to extract waste heat from exhaust cold indoor air and deliver this energy to the hot outdoor fresh air [7]. Figs. 1 and 2 depict the sketch diagram and form of the separate heat pipe heat recovery facility, which has an evaporator and condenser section where the working fluid evaporates and condenses respectively. The condenser section is located above the evaporator so that the condensate is returned by gravity. The vapor ascending and condensate descending tubes are jointed through copper tube. It is well known that water is excellent as a working fluid for heat pipes because of its high latent heat, its availability, and its high resistance to decomposition and degradation [7,14,15]. Because of the incompatibility with iron, however, copper was selected initially as the container material. Fig. 3 shows the configuration of the separate looped heat pipe (the left frame). The evaporator section of the heat pipe consists of one bank of externally finned heat pipes, the same as the condenser section. The ventilation duct is mosaic with the fins of adjacent two heat pipe units, as presented in Fig. 2 (the right frame). The indoor exhaust gases are extracted by axial fan and discharged to the ambient atmosphere after heating through the condenser section; the fresh air is supplied to the inside room after pre-cooled [16]. The window-type air conditioner and heat recovery facility are combined together to be a new energy saving air conditioner as shown in Fig. 4.

Liu et al. have developed a one-dimensional steady-state model to calculate the upper and lower critical values of the separate heat pipe operation envelope as a function of the initial filing ratio, type and vapor temperature of working fluid, separate heat pipe dimensions and the operation power throughput [7,15]. The

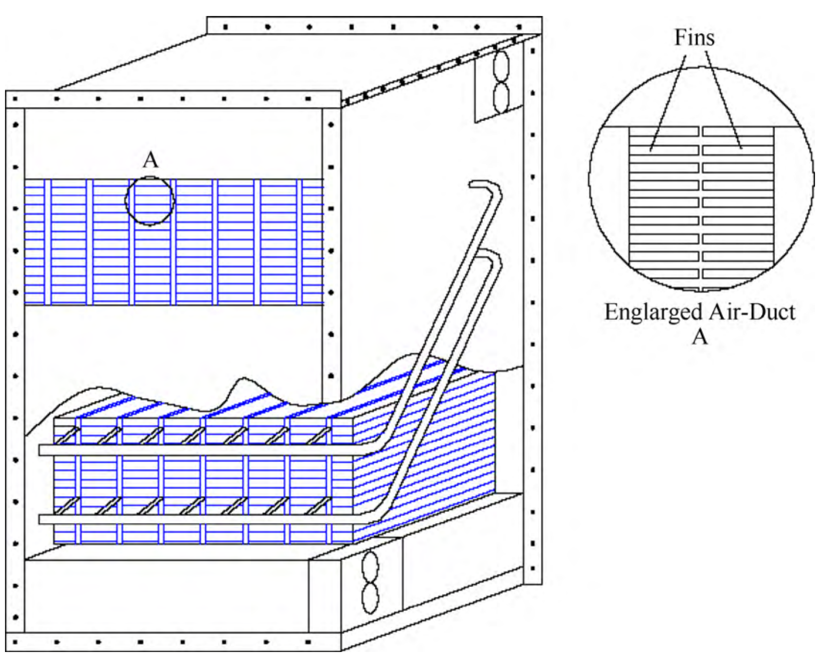


Fig. 3. Configuration of separate looped heat pipe Liu et al. [7].

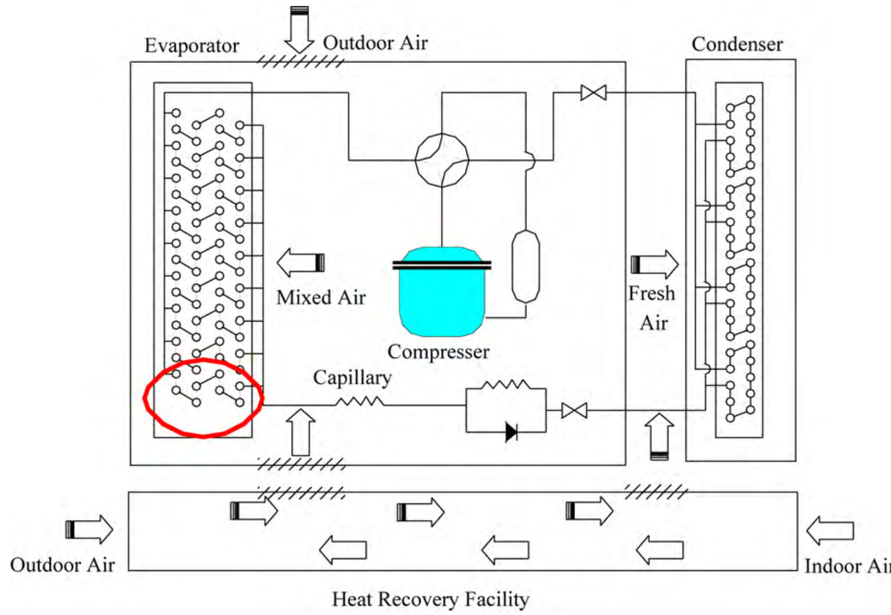


Fig. 4. Schematic diagram of the window-type air conditioner with heat recovery facility from Liu et al. [16].

results of parametric study show that increasing the hydraulic diameter should significantly raise the upper critical values of initial filling ratio and slightly extend the lower boundary. The type of working fluid and the vapor temperature can influence the critical liquid film thickness. The liquid film thickness would become thinner along with increasing the vapor temperature and access to the lower critical value of initial filling ratio. Moreover, operation envelopes of the separate heat pipe depend on the working fluids.

Frosting of this window-type air conditioner with heat recovery facility has also been investigated [16]. One-dimensional mathematical model was used to calculate the unsteady thermal characteristics of fin and tube evaporator under forced convection condition. With the heat recovery facility, temperature of the mixed air, i.e. evaporator inlet air temperature, would increase, while in terms of relative humidity, would depend on the properties of the indoor air and outdoor air, and their ratios. Rationalizing ratio and characteristics of indoor and outdoor air could prolong frosting time and reduce the frost growth greatly. The parametric studies show that total heat transfer coefficient, frost thickness, and air side pressure drop are all decreasing functions of the inlet air temperature, but increasing functions of relative humidity. A higher air mass flow rate can accumulate less frost.

Fig. 5. Form of the membrane core from Yang [19].

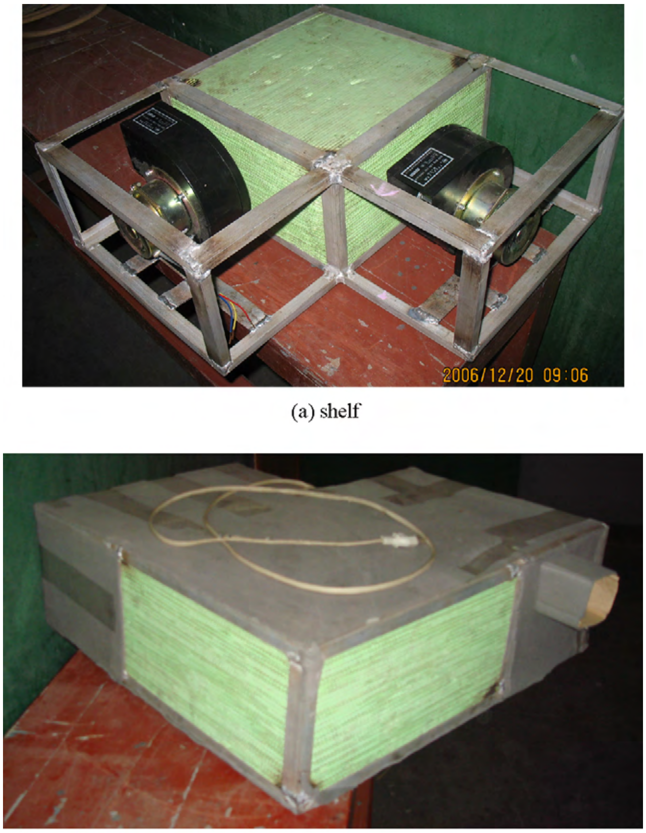
2.2. Membrane-based total waste energy recovery ventilator

The membrane-based energy recovery ventilator has the following salient features: simultaneous recovery of sensible and latent heat, high heat and moisture exchange effectiveness, no mechanical components [17,18]. In this case, a membrane-based total energy ventilator is used before the fresh air is pumped to an air conditioner for temperature reduction and air dehumidification [17–19].

Fig. 5 shows the membrane core in the heat recovery ventilator. The membrane is useful in separating moisture from the vapor/air mixture owing to their strong affinity to the water molecule. The strong affinity also leads to a high permeation difference between water and air. The permeability ratio of water to air ranges from 460 to 30,000. In other words, gases other than vapor can hardly permeate through the membrane. These features have led to the present membrane-based energy recovery ventilator, in which both the sensible heat and the moisture are transferred simultaneously through the membrane [17,20–23].

The membrane-based energy recovery ventilator is just like traditional plate-type heat recuperator. The only difference is that hydrophilic membranes are used in place of metal plates. A cross-flow membrane-based energy recovery use two air streams, the supply and the exhaust, to flow in thin, parallel, alternating membrane layers in order to transfer heat and moisture from one air stream to the other. The membrane-based energy recovery ventilator is composed of membrane core and two centrifugal fans. In order to reduce the total weight of the membrane-based energy recovery ventilator, the aluminum is adopted to be the shelf of the membrane core and fans. The outside fresh air and exhaust indoor air are entranced into the thin, parallel membrane core layers in order to transfer heat and moisture from one air stream to the other. The form of the whole system is shown in Fig. 6. It is worth noting that the membrane core must be tightly connection with the aluminum shelf, and therefore it is sealed by the edges of the shelf.

The performance of the membrane-based energy recovery ventilator has been investigated [19]. The differences of indoor air, outdoor air and supply air have been indicated in terms of their temperature, humidity and enthalpy. The energy recovery efficiency and energy efficiency ratio are also computed as an evaluation of the energy recovery performance. The experimental



(a) shelf

(b) with insulation layer

Fig. 6. Form of the membrane-based energy recovery ventilator from Yang [19]. (a) Shelf and (b) with insulation layer.

results show that temperature, humidity and enthalpy differences between supply air and ambient air generally increase with the enlarging differences between the indoor and outdoor air. So does the energy recovery efficiency. However, the latent heat recovery of the membrane-based ventilator reduced after a long operation period, even if the humidity difference between indoor and outdoor air increases. This may due to the hydrophilic limitation of the membrane cores [17,20–23].

3. Thermoelectric technology application in low-grade energy recovery

As aforementioned states, low-grade energy can be recovered to enhance the efficiency of energy consumption. Actually, there have been lots of low-grade energy recovery methods, depending on actual situations, usually including heat recovery exchanger, traditional heat pump, thermoelectric heat pump, adsorbing system, etc. [7,15,16,24–26]. Thermoelectric heat pump is thought to be one of the most promising technologies that are in global concern for energy conservation and environmentally friendly to take place the traditional heat pump for avoiding their high noise levels, compressor vibration, and excessive weight and size [24–26].

Since thermoelectric devices have no moving parts, there is nothing to wear out and generate noise. Additionally, there is no refrigerant to contain so the problem of handling a two-phase change over is simplified. Concomitantly, ozone layer hazard is avoided. Pressure-tight tubing is replaced by electrical wiring. The heating and cooling functions of the thermoelectric system can be interchanged by reversing the polarity of the direct current.

Thermoelectric application in buildings could be competitive for its novel character. The thermoelectric modules' hot and cold sides could be simultaneously occurred when a direct current supplies. In this section, a closed-type thermoelectric clothes dryer, a thermoelectric domestic ventilator, a combined thermoelectric heat pump water heater and a thermoelectric vehicle air conditioner, a thermoelectric enhanced CPU cooler and a thermoelectric dehumidifier will be illuminated, respectively. All of these have been investigated experimentally by present authors.

3.1. Closed-type thermoelectric clothes dryer

Particularly, thermoelectric dryers (TED) work using the Peltier effect; i.e., when a DC current passes through a cell made of a pair of n- and p-type semiconductor materials, one of the junctions will be cooled while the other is heated depending on the direction of the current [27,28].

Fig. 7 presents the schematic diagram of the closed-type clothes dryer. When DC current was applied to the thermoelectric drying system, the Peltier cells absorbed heat from the metallic block outside the drying cabinet and dissipated heat to the heat sink, thus creating a heat flux between the junctions of two different types of materials. On the hot side, heat was rejected to the circulating air. The heated air from the hot side of the thermoelectric unit was passed through the drying chamber to dry the clothes installed for test. After the drying process, the moist air stream leaving the drying chamber was diverted through the cold side of the thermoelectric unit, where it was cooled, and dehumidification took place as heat was given to the hot side. According to the psychrometric chart, circulated hot air–vapor mixture became saturated and condensation occurred when contacting the cooled surface of the finned cold side of the thermoelectric unit. The condensed water from the moist air was collected into the drop receiver. After being forced to pass through the cold side of the unit, the dry and cooling air was heated by its hot side, with air temperature asymptotically approaching to the set one. Upon that, sufficient latent heat of evaporation of water vapor from the clothes samples was provided. Water vapor diffused through a boundary film of air and was carried away by the moving air. The dehumidified and heated air was then returned to the drying chamber. Consequently, the efficiency of this thermoelectric dryer is greatly promoted such that it is greater than that of a conventional electrical dryer [25,29].

The physical domain considered here was composed of two aluminum substrates and 40 thermoelectric elements sandwiched between two substrates as shown in Fig. 8. The system consisted of two main sections, namely (1) a thermoelectric unit and (2) a drying chamber with an opener mechanism connected in series to the thermoelectric unit. The main components of the thermoelectric unit were the junctions of the thermoelectric elements, while the drying chamber was a hexahedron with dimension of 1000 mm × 520 mm × 400 mm and with weight of 22 kg. The holes on the perforated tile allowed the drying air to pass through

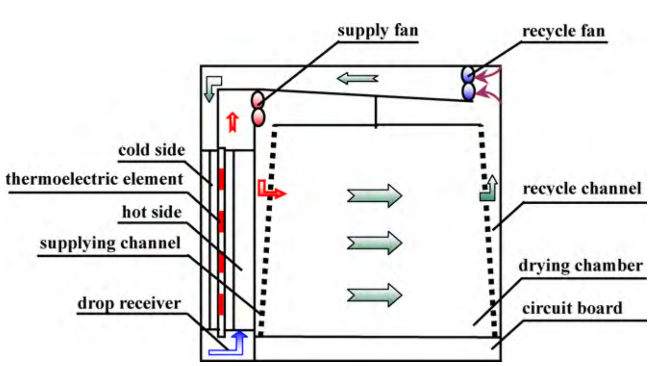


Fig. 7. Schematic diagram of the thermoelectric clothes dryer from Liu et al. [25].

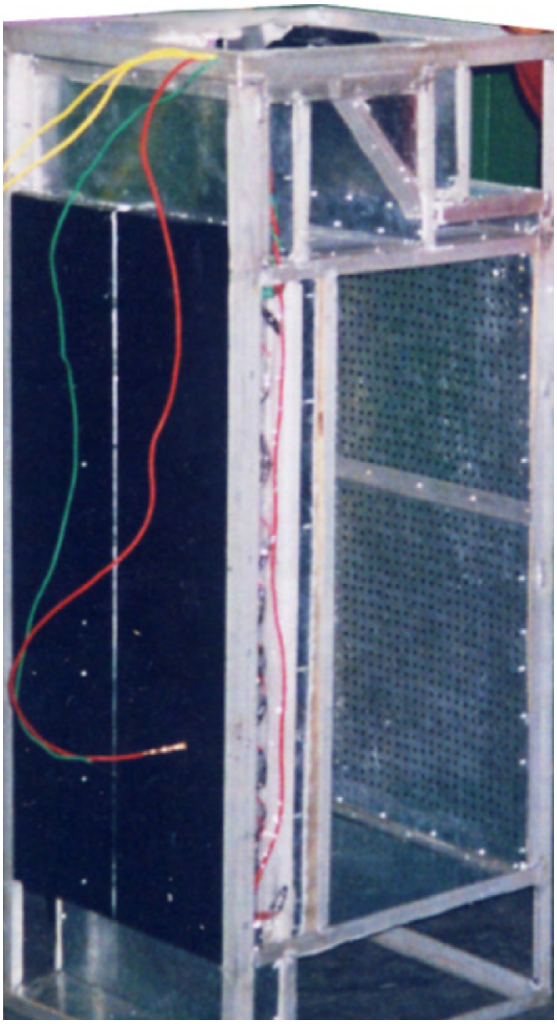


Fig. 8. Inner structure of the thermoelectric clothes dryer from Liu et al. [25].

the hexahedron and recirculate uniformly. An aluminum beam was chosen as the frame of clothes dryer because of its rigidity and lightweight properties. Synthetic plastic hanger frames were utilized for hanging the clothes. As described in Fig. 8, when a DC current is applied, heat is moved from one side of the device to the other, where it must be removed with a heat sink. The effectiveness of the heat sink is crucial to the operation of TED. The heat sink should be designed to not only minimize the thermal resistance but also remove amount of heat from the junctions. Additionally, heat storage capacity of the heat sink should be improved as high as possible, which effectively maintains the heat sink temperature lower than the junction temperature. Furthermore, the supply and recirculating channels were made triangular in shape. This was done to obtain uniform air velocity distribution at both the top and bottom sides of the drying chamber as depicted in Fig. 8. The aluminum substrates mounted on the experimental apparatus were identical and were 1000 mm long, 520 mm wide, and 20 mm deep. In terms of infinite surface radiation between the two large surfaces of the substrates, heat transfer from the hot side to the cold side could occur, which has been significantly inhibited through embedding 14-mm-thick polyurethane foam in the gap between thermoelectric elements. The base and sides of the drying chamber were covered with 13-mm thick plywood to reduce the heat transfer between the test chamber and surroundings. The present TED system was run in the form of an air recycling system, not an open system. The open system would directly entrain moist air of high humidity [24,25].

A mathematical model of heat transfer, based on one-dimensional treatment of thermal and electric power, is conducted [25]. The cooling and heating productions are both correlated in terms of electric resistance, thermal conductivity, and electric current. Experimental investigation on drying of clothes has been attempted, covering the drying air temperature, initial-input electric power, and total weight of wet clothes, with drying rate and specific moisture extraction rate as evaluating indexes. Generally, the drying rate was found to increase first and decrease afterwards as time decayed. Analytical and experimental results demonstrate that optimal performance of the thermoelectric dryer strongly depends on intensities of these operating parameters [25].

3.2. Thermoelectric domestic ventilator

The thermoelectric ventilator is composed of two centrifugal fans, a flat-fin cross flow sensible heat exchanger made of aluminum, air duct, a thermoelectric modules heat exchanger made by thermoelectric modules and flat-fin heat sinks made of aluminum. Differing from market available ventilators with passive heat recovery, this ventilator was integrated with a flat-fin cross flow sensible heat exchanger and a thermoelectric modules heat exchanger to enhance heat recovery from exhaust. This ventilator's overall dimension was 400 mm $\times$ 310 mm $\times$ 260 mm [26,30].

As shown in Fig. 9, a cross flow sensible heat exchanger and a thermoelectric modules heat exchanger were made in cubical shape separately. Air tunnel of inlet and outlet were connected by air ducts in order to collect condensed water from air and reduce the ventilator's pressure loss. Thermal conduct grease was coated in the contact surface of modules and sinks so that the contact resistance and cold bridge can be reduced as small as possible. Heat sinks and modules were jointed into a whole body with screw bolts with thermal insulating casing. Thermal insulating material was filled on the surface of the thermoelectric heat exchanger. Thermal insulation was Armaflex with 5 mm thick and a conductivity of 0.03 W/m k. Total mass flow rate of three people (typical Chinese urban family due to family born plan) was considered here being a household application. Air volume of this ventilator ranged from 60 to 70 m^3/h. Two centrifugal fans with high pressure were chosen, with standard gauge values: 120 m^3/h, 140 Pa, 58 W, 0.16 A, 2000 rpm, 50 db. There were 10 thermoelectric modules used with type of TEC12706. Every two modules were in serial as a team and five teams were in parallel as a whole.

The performance of the thermoelectric domestic ventilator was investigated during summer and winter seasons. Three ventilation speed, i.e., high, medium and low were adjusted in our experiments. Experimental results indicate that the coefficient of performance (COP) is a decreasing function of input voltage under the same ventilation speed. The maximum COP was gained with the input voltage of 8 V, however, the maximum heating power occurred under 12 V. The exhaust temperature difference and fresh air temperature difference are also recorded in order to evaluate the heating and cooling performance of the ventilator [26,30]. Generally, the ventilator can run with the COP over 2.5 both in summer and in winter. Its optimum working parameters were found through the test. Moreover, further improvements in terms of COP and cooling and heating performance may be possible through improving thermoelectric module contact-resistances, thermal interfaces and heat exchangers.

3.3. Integrating thermoelectric heat pump and heat pipe water heater

An instantaneous water heater prototype has been developed by means of integrating a thermoelectric heat pump with a separate heat pipe, as presented in Fig. 10 [31,32]. The separate

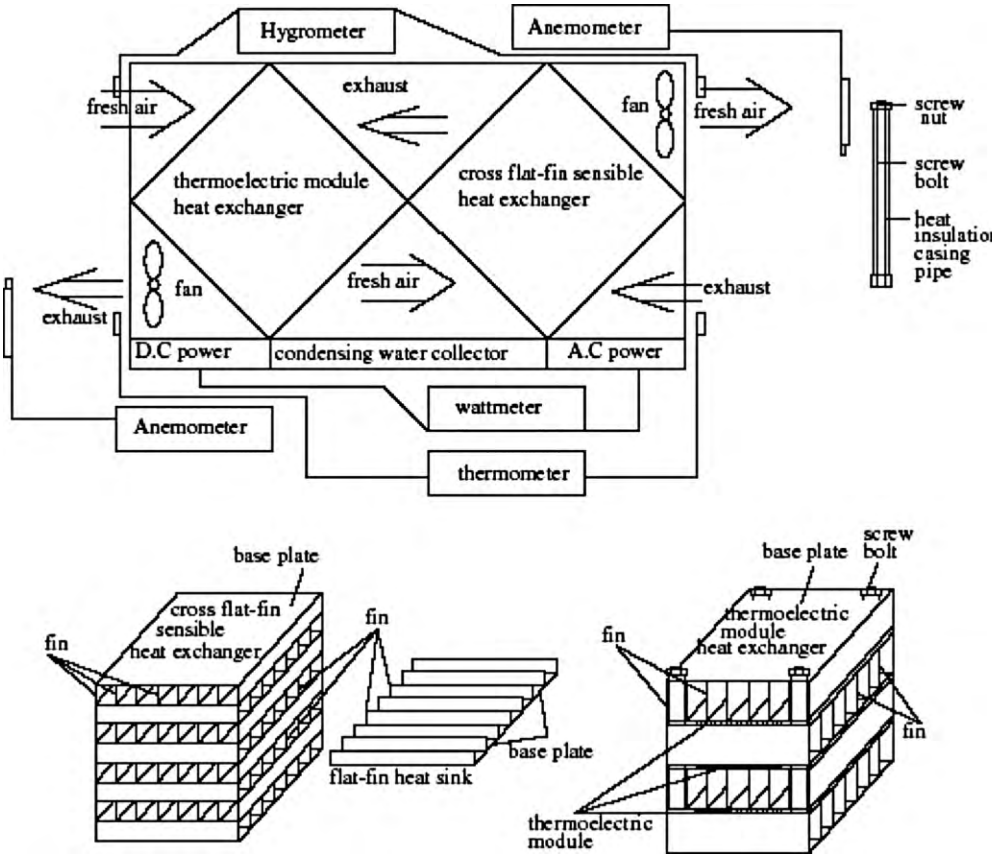


Fig. 9. Schematic diagram of thermoelectric domestic ventilator from Tang et al. [30].

wickless heat pipe was filled with acetone as working fluid and it was composed of evaporator, vapor pipe, condenser and condensed liquid pipe. The evaporator is embedded in the floor to absorb energy of exhaust/waste hot water and to save bathroom space.

The operating principle is as follows: during the period of energy collection, the exhaust hot water heats acetone in the heat pipe evaporator. Thermal buoyancy leads to natural circulation within the heat pipe. Acetone is boiled away, rises and passes through the vapor pipe into the condenser, where heat flows into the cold side of the thermoelectric heat pump. The acetone vapor condenses into liquid while rejecting heat, which heats supply tap water together with the energy consumed by thermoelectric modules in the hot side of thermoelectric heat pump [31,32].

The performance test of the thermoelectric heat pump has been conducted in this work. Tests consist of three groups with different parameter variations, namely: (i) flow rate of working mediums (tap water); (ii) temperature difference between working mediums; (iii) electricity input of thermoelectric modules.

Heating performance of the thermoelectric heat pump with respective variations of flow rate of working medium was presented. Increasing flow rates intensified the heat exchange between exchangers and mediums, and the thermoelectric heat pump performance tended to be better further. Since heat flux on hot side is times of the value on the cold side, variation of flow rates on hot side affected the thermoelectric heat pump performance more noticeably than that on cold side. The performance of thermoelectric heat pump is also affected by the mean temperature difference between heat mediums on two sides. This has been conducted [32]. Increasing mean temperature difference of working mediums resulted in linearly decreasing of COP of the thermoelectric heat pump. The decreasing amplitude was remarkable as the electricity power input of thermoelectric modules decreased.

The coupled performances of the thermoelectric heat pump and heat pipe water heater have been evaluated comparing with

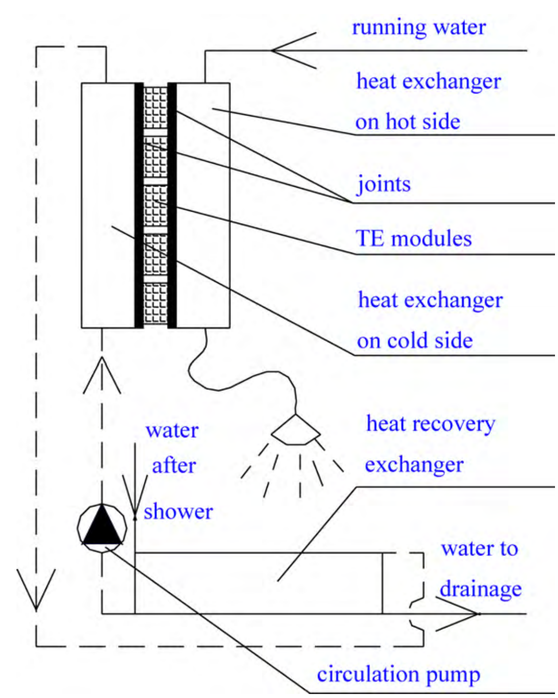


Fig. 10. Schematic diagram of integrating heat pipe and thermoelectric water heater from Tang et al. [31].

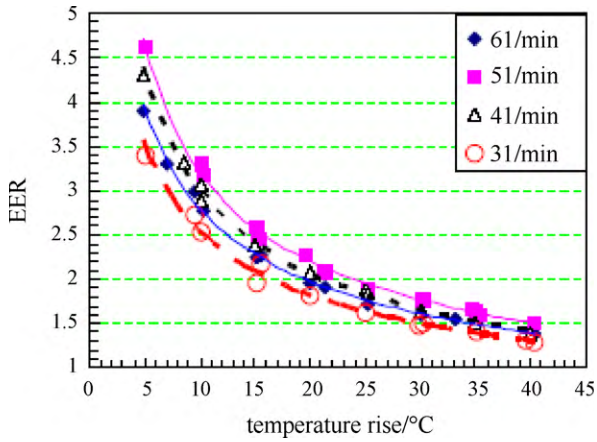


Fig. 11. Performance of TE heat pump water heater for different flow rates from Luo et al. [32].

conventional electrical water heaters [32,33]. The energy efficiency ratio (EER) of this novel device is also calculated as presented in Fig. 11. The EERs reached 1.45 or more, even if the temperature increment of supplying water reached 40 °C. Comparing with the up-to-date electrical water heaters of EER equaling 0.9, the present prototype can reduce more than 38% of the electricity power consumption, with satisfying the demand of supplying hot water across the whole year.

Additionally, the EER of our present device will achieve the highest as the flow rate of supplying water flow rate is 5.0 l/min, while it reached the minimum when that flow rate decreased to 3.0 l/min [32]. Absolutely, the performance of our present device should be enhanced further, through dropping off some existing manufacturing flaws.

3.4. Thermoelectric vehicle air conditioner

The schematic diagram of thermoelectric vehicle air conditioner is shown in Fig. 12. The major components of the thermoelectric air conditioner include: thermoelectric module, air duct, aluminum plates, finned surface (or heat sink), and fan. In this study, 28 thermoelectric modules with type of TECl127085 were used in the design of the air conditioner. A compact fin heat sink ensured heat transfer between the faces of thermoelectric modules and air. It was built from six folded sheets of aluminum, forming a network of 6 channels. Each channel was 10 mm deep, 220 mm wide and 400 mm long. The walls were 0.2 mm thick. Thin copper sheets of 0.6 mm thick and thermal grease were placed between the folded sheets to enhance thermal contact [34–36]. Copper sheets were added to the sides of the cabinet of the air conditioner to evenly distribute the cold for a uniform temperature distribution within the whole air conditioner channel. The plastic plates were used as thermal insulation for inhibiting the back flow of heat when operating in humid conditions.

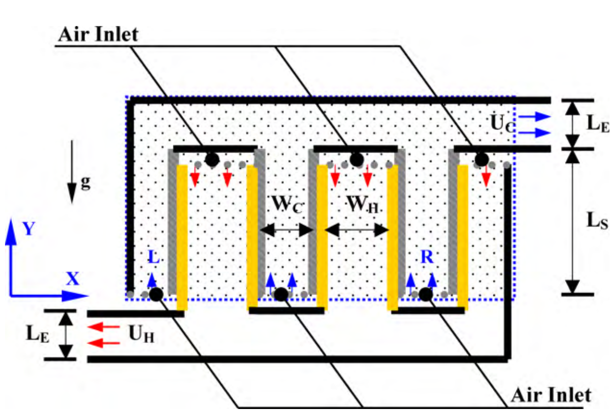


Fig. 12. Schematic diagram of thermoelectric vehicle air conditioner from Zhao et al. [35].

The interconnection of the finned heat exchanger (or heat sink) and aluminum slabs established the air paths, through which cooled or heated air was discharged to the indoor spaces or outside. An axial fan connected to the far end of the duct induced the air. An insulating material was used to prevent heat conduction from the hot side to the cold side and the ambient environment. The cross air paths between the hot sides and cold sides were produced to enhance heat absorbing and emitting. The appearance of the thermoelectric vehicle air conditioner is presented in Fig. 13 [34,35].

Effects of five parameters on the performance of air-conditioning system were assessed experimentally, namely, the air flow rate, the input current, the outside air temperature, the current direction, and the insulation layer thickness. An ammeter and voltmeter quantified the electric power supplied to each thermoelectric module. Pressure drops were measured between the inlet and the outlet of the fin heat sink through a level difference of liquid in a U tube.

The experimental results showed that the cooling capacity increased with air velocity, while it dropped with decreasing temperature of supplying air at the hot side inlet. Present configuration offered the advantages of rapidly changing between heating and cooling through reversing current direction [37]. These results completely demonstrated the feasibility of cooling or heating airflow by means of thermoelectric modules. Both for cooling and heating, the greater the intensity results in the lower the temperature of the cold side and the higher the temperature on the hot side. Furthermore, we found that the thickness of the insulation layer is one of the important factors of affecting the performance of the thermoelectric vehicle air conditioner. Firstly,

Fig. 13. Sample machine of thermoelectric vehicle air conditioner from Tang et al. [34].

on one side, the thicker the layer is, the less energy transfers from the hot side to cold side. On the other hand, increasing the thickness of the insulation layer can simultaneously reduce the heat transfer between cold side and air. Therefore, an optimal thickness of insulation layer should be determined. Experiments with the module thickness of 10 mm, 14 mm, 27 mm, 38 mm were conducted and the module of 14 mm thickness tended to be the best one in terms of cooling and heating capacity.

3.5. Thermoelectric mini-cooler coupled with heat pipe for CPU

Recent years, electronic computers become more compact and higher capacity of operation, which results in the difficulty of heat dissipation from smaller CPU surfaces [37–41]. Thermoelectric mini-cooler coupled with heat pipe for CPU has been designed and constructed as shown in Fig. 14 [40].

The thermoelectric cooler consisted of a thermoelectric module, a heat sink connected to the hot side, and a cooling-load heat exchanger connected to the cold side. The thermoelectric module comprised many pairs of p–n type thermoelectric material connected in series and clamped and soldered with two base plates [41]. The cold side of the thermoelectric cooler is directly attached to CPU chip. A looped heat pipe heat exchanger is attached to the hot side of the thermoelectric cooler as a heat sink. An axial fan is installed above the heat sink to blow the heated air to the ambient. Heat pipe uses the high latent heat of vaporization of liquids, which makes it possible to ensure an intensive heat removal in the evaporation zone and to have a relatively small mass flow of a working fluid inside the device. The thermoelectric module was pasted on the heat pipe with silica gel to ensure no sliding. The thermoelectric and heat pipe modules employed in this study were readily available off-the-shelf modules purchased from TE Technology, Inc. and Thermaltake, Inc., respectively. The looped heat pipe is made of two sealed U tubes with diameter of 8 mm, which operates on the closed evaporation–condensation cycle with use of the gravity forces for the working fluid circulation. The heat sink is made from a copper finned heat exchangers with 80 mm × 80 mm base plate (6 mm thick), 4 mm fin pitch, 45 mm × 80 mm fin size (1 mm thick), and 52 fins [42]. It is evident that an increase in the hot side surface area will result in better cooling potential. The thermoelectric modules were attached to the heat sink by the use of special high temperature thermal grease, which has great heat conductivity to minimize thermal contact resistance.

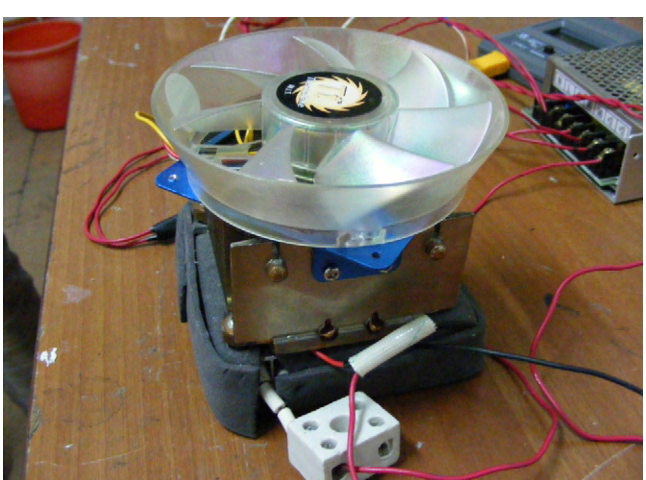


Fig. 14. Prototype of mini-thermoelectric cooler coupled with heat pipe for CPU from Xie [40].

Fig. 15. Testing system of mini-thermoelectric cooler coupled with heat pipe from Xie [40].

Performances of thermoelectric mini-cooler coupled with heat pipe were measured using a test-rig system, where a heated aluminum block as a heating source was included. Interfaces of the aluminum blocks and the thermoelectric modules were instrumented with thin thermocouples, which are employed to measure temperature distributions. The photograph of the thermoelectric mini-cooler coupled with heat pipe testing system is presented in Fig. 15. Effects of thermoelectric module operating voltage, heat source intensity and thermoelectric module quantity on the performance of the test-rig system were investigated. Different combinations also are compared, i.e., thermoelectric cooler coupled with heat pipe heat exchanger and thermoelectric cooler coupled with plate heat exchanger. The coefficient of performance (COP) of the system with heat pipe is much greater than that with plate heat exchanger. The experimental results showed that the performance of heat dissipation from hot side is a vital important factor to the whole system. Performance of the whole unit will be enhanced greatly with more heat can be dissipated from the hot side of thermoelectric modules. Actually, the cold side can be maintained lower temperature only if sufficient heat transferred from the hot side can be dissipated.

3.6. Thermoelectric dehumidifier

In past decades, dehumidifying technology has been pushed by the development of agriculture, industry and built environment etc. However, dehumidifying using the thermoelectric cooling principle has drawn fewer attentions [25,43–46]. The technology of thermoelectric cooling always accelerates the development of the thermoelectric dehumidifying. Its operation is based on the absorption of heat from the cool side of a Peltier module, which cools and dehumifies air in contact with it.

The design of the humid-air flow channel allowed the use of existing models for one-side transfer in a rectangular channel. The channel was made of aluminum plate and insulated by the plastic sheet. The cross-section of the channel is 26 mm × 70 mm, and an axial fan (80 mm × 80 mm) is introduced at the end of the channel, which can entrain air from ambient environment. A convergent rectangular channel is needed here to connect the different cross-section channel with central angle of 12°. When heat absorption is initiated, the temperature of the air in contact with the cool side decrease to dew point, and liquid water starts to form. This requires the warm side temperature is greater than 65 °C, and results in the cool side temperature no greater than 0 °C. The heat is rejected at the hot side of the Peltier module through the heat pipe by means of a heat extender and dissipater as shown in Fig. 16.

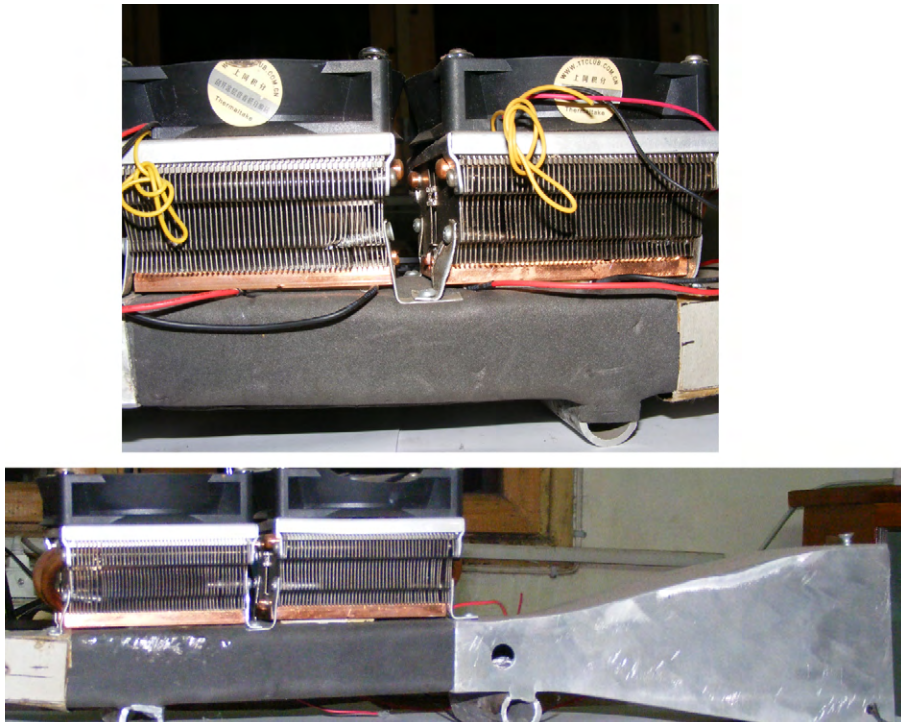


Fig. 16. Prototype of thermoelectric dehumidifier from Xie [40].

Both the heat absorbed and heat dissipated are functions of the Peltier module voltage and therefore, there is an optimum voltage that minimizes the time required for the formation of the condensation. Two thermoelectric dehumidifiers connect in series along the heat flow channel to enhance the dehumidifying process. Humid fresh air goes through the first stage of dehumidification at first, and passes through the second stage cold exchanger, therefore, it cools down yet further and undergoes a second stage of dehumidification. The Peltier pellet and fan supply voltages are provided by independent power supplies. This offers greater flexibility when it comes to performing tests aimed at optimizing these control settings.

The use of thermoelectric technology means that temperature and humidity can be controlled more accurately as the electricity power of the device can be regulated by simply varying the supply voltage. This makes the device attractive for those applications which call for temperature and humidity precision, such as in laboratories, hospitals, etc.

The dehumidification performance of the thermoelectric dehumidifier has been investigated. The measurement system consists of anemo-thermoscopes (Swema Air 40), a digital hygrothermograph (WSB-1/WSB-2), and a dynamometer (D26-W). The control Peltier supply voltages were then optimized by experimentation. Numerous tests were carried out for atmospheric conditions of temperature 35 °C and relative humidity 80% by varying the thermoelectric input voltages on the prototype in a climatic chamber. Control settings for optimum condensed water flow rate were obtained. Test results illuminated that the decreasing of the thermoelectric input voltage resulted in the increasing of COP. This is due to the fact that limit condensation water can be obtained when air flows through thermoelectric cold side with high speed even under different thermoelectric input voltage condition. However, the relative humidity reduces 10% under this condition. This further demonstrated that the thermoelectric dehumidifier can work at certain region with high relative humidity.

4. Conclusions

The technologies of low-grade thermal energy recovery for refrigeration, heating and dehumidifying are promising. Waste heat and cold recovery facilities in air-conditioning room and thermoelectric technology are employed to perform the low-grade energy recovery.

Novel energy conservation window-type air conditioners were designed and built combining with waste heat recovery facility. Pre cooling/heating fresh air is an effective way to simultaneously enhance ventilation and energy conservation, which is the final objective of this thermal energy recovery window-type air conditioner for an occupied open-plan space.

High heat transfer efficient heat pipe and membrane-based plate total heat exchanger were adopted as heat recovery facility. Both of them have advantages of no moving parts, high energy efficiency, low noise level, etc. With the technology development, the cost of producing electricity power with heat recovery refrigeration is falling. If the costs of fossil fuels, transportation, energy conversion, electricity transmission and system maintenance are taken into account, the cost of energy produced by combined system with waste heat recovery would be lower than that for conventional refrigeration systems.

In addition to the waste heat recovery, active exploitation of ambient air energy is also presented with thermoelectric technology. Of the several kinds of thermoelectric heating/refrigerating systems analyzed in this paper, the intermittent system has been extensively studied experimentally, owing to its simplicity and cost effectiveness. However, the main disadvantages such as low heat transfer effectiveness have precluded commercial production of the system at present time. Hence, more efforts should be made to enhance the COP of these thermometric units, such that the thermoelectric technology and relevant applications can compete with vapor-compression technologies.

Up to date, technologies of heat recovery, mass recovery and multi-stage recovery are promising for improving the COP of

thermoelectric units. Thermoelectric technology combined with other technologies for more effective and multi-purpose applications seems to be a new trend in energy conservation research. This will extend the area of applications of thermoelectric technologies and make the thermoelectric refrigeration, heating and dehumidifying more cost effective and more feasible.

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